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Accelerator Breeder Concept (AECL-6363)

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ACCELERATOR BREEDER CONCEPT

by

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Concept de l'accélérateur surrégénérateur

par

G.A. Bartholomew, J.S. Fraser et P.M. Garvey

Résumé

On décrit les principaux composants et les fonctions d'un accélérateur-surrégénérateur. Dans les grandes lignes, on décrit le rôle de l'accélérateur-surrégénérateur comme installation d'appoint possible de production à long terme de matières fissiles pour les cycles de combustible CANDU* avancés au thorium et le programme de R&D canadien mis sur pied pour réaliser cette installation.

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*CANDU: Canada Deutérium Uranium

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ABSTRACT

The principal components and functions of an accelerator breeder are described. The role of the accelerator breeder as a possible long-term fissile production support facility for CANDU (Canada Deuterium Uranium) thorium advanced fuel cycles and the Canadian research and development program leading to such a facility are outlined.

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1. INTRODUCTION

Accelerator breeding is one of two processes in prospect today for electrical breeding of fissile material, the other being fusion.

The CANDU* self-sustaining equilibrium thorium cycle can achieve little in excess of unit conversion ratio1) and therefore any fissile material needed for initial inventory of new reactors or for topping enrichment that may be required to achieve minimum total unit energy cost in a thorium-fuelled reactor economy must be supplied from external sources. The accelerator breeder is thus envisaged as a long-term fissile production support facility for CANDU thorium advanced fuel cycles that may be needed in the eventuality that shortages develop in separated ^{235}U and plutonium supply.

The principal components of an accelerator breeder are shown in Fig. 1. An accelerator, usually in current concepts a proton linear accelerator, delivers a high-current beam of charged particles to a thick target surrounded by a blanket assembly. The beam interacts with the target to produce an intense source of neutrons by the spallation process. The neutrons are multiplied and absorbed in fertile material in the blanket.

In the spallation process a bombarding particle, typically a 1 GeV proton, strikes a heavy-element nucleus and ejects several "cascade nucleons" with energies of the order of 100 MeV each. The residual nucleus cools by evaporating neutrons with mean energy about 3 MeV, and may eventually fission. The cascade nucleons may repeat the process in other target nuclei. Some fast neutrons produced may cause fast fission or

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*Canada Deuterium Uranium

(n,xn) reactions. The net effect for a 1 GeV proton bombarding a thick uranium target enriched to 2% ^{235}U* is the production of about 50 neutrons and 4 GeV of heat$^{2)}$. In a thick Pb-Bi target surrounded by a 2% enriched blanket of uranium these numbers are about 25 neutrons and 2.6 GeV of heat$^{3)}$. Figure 2 shows the neutron yield and heat produced with ^{238}U and Pb targets as a function of proton energy. Additional heat can be produced to any arbitrary level by building-in fissile material in the target assembly.

Current assessment in Canada places accelerator breeding ahead of fusion breeding in practicability but this outlook could change under the impact of the vastly greater worldwide effort in fusion development.

Perceived technological advantages of accelerator breeding are:

- accelerator systems of the type required have been demonstrated, although not at the beam power required,
- the target/blanket is inherently safer than a fast breeder reactor because it can be operated as a sub-critical device; the power density in the blanket can therefore be lower than for a breeder and the risk from a loss of coolant accident correspondingly lower.
- the neutronic (target/blanket) part of the system is separate from, and unencumbered by, components relating to the electrical (accelerator) part of the system; hands-on maintenance of the accelerator may be practicable. Simple reactor-like geometries in the target region should make for simple remote handling operations in this region.
- no tritium-breeding and recycling are required,

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*Level of enrichment induced by bombardment midway in target exposure.

- no "burn conditions" need be met or exceeded; the production rate is to first order simply proportional to proton beam power (ignoring any compounding effects from fissile build-up)
- the average neutron energy is near 3 MeV and therefore neutron damage "first wall" effects may be somewhat relaxed compared to fusion where the average energy is somewhat lower than the incident energy of 14 MeV,
- development of the accelerator can proceed in stages beginning at low energies with each succeeding stage incorporating the preceeding one.
- the fuel producer is decoupled from the energy producer (reactor) so that shutdown of the breeder need not impede availability of the reactor as in the case of fast reactor breeders.

Disadvantages of the accelerator breeder at the current stage of development are mostly in the target blanket area:

- conceptual design of the target is at an early stage,
- materials damage, heat transfer, and structural design problems in the target area may be formidable.
- Methods of testing target-blanket performance are likely to be inadequate short of building the full accelerator-target complex.

Accelerator breeding began in the United States with the development program on the MTA accelerator[4)] in the early 1950's. In the MTA process a 500 MeV, 320 mA deuteron accelerator with a primary beryllium target surrounded by a secondary depleted uranium target was planned to produce about 500 kg of plutonium per year. In Canada, almost concurrently, Lewis5) realized the value of accelerator breeding in the power program and initiated spallation neutron yield measurements with the McGill cyclotron6) and cosmic ray protons7). The Intense Neutron Generator (ING) project at CRNL* 8,9) was based on the concept of a high-power proton beam bombarding a liquid lead-bismuth eutectic target, with the goal of producing a high flux of thermal neutrons for research purposes. In connection with that study, spallation yield measurements were carried out on the Brookhaven Cosmotron10) and the Birmingham cyclotron11). The ING program was terminated in 1968 and associated development activity switched to shorter-term projects that would, however, maintain expertise for possible eventual application to accelerator breeder development. Concurrent with the ING program there was a strong interest in spallation at Oak Ridge10,12,13) and in the Soviet Union14-17). Recently, further studies have been made in the Soviet Union18) and in the United States19-22). The present program in Canada is described in section 9.

This paper will discuss the accelerator breeder concept as a support facility for CANDU thorium fuel cycles. Fuel reprocessing will be assumed to be identical to that for CANDU and proliferation resistance will be considered in the context of the overall cycle. Since the accelerator breeder is still largely in the design concept stage it will be possible to provide only a rough outline of its characteristics.

2. CONCEPTUAL DESIGN

In this paper it is assumed that the accelerator delivers to the heavy element target a beam of protons with energy 1 GeV

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and current 300 mA ($\sim$1.9 x 10^{18} protons per second) generating a neutron source of the order of 10^{20} neutrons per second. Such a source could yield in the neighborhood of 1 Mg/a of fissile material in a suitable blanket.

The choice of beam particle is limited to isotopes of hydrogen; for higher atomic numbers energy losses by electronic excitation in the target are greater. A case can be made for favouring deuterons over protons21). Indeed, deuterons produce a neutron yield exceeding that for protons by as much as 25-30% below 1 GeV but diminishing with higher energies to 5% at 2 GeV18). However, this advantage is offset by a four times more stringent limit on the beam current that can be transmitted owing to space charge effects, and by much increased activation by D(d,n)p neutrons induced by spilt beam in the low energy parts of the accelerator. For these reasons most present conceptual designs19) are based on proton acceleration.

The choice of beam parameters (current and energy) to achieve a given fissile production rate depends on economic factors in system design and the neutron yield set by the materials and geometry of the target. The beam parameters adopted here were derived from a broad-brush consideration of system costs. Figure 3 shows the fissile product cost as a function of proton energy for various production rates23). The curves indicate that for high enough production rates a shallow mimimum is reached around 1 GeV. Some matters requiring further experimental test, in particular the problem of handling high current beams at the low-energy end of the accelerator, might result in a small cost penalty for high currents thus forcing the selection of a lower current than 300 mA with a compensating higher output energy than 1 GeV.

2.1 Accelerator

Figure 4 shows the major dimensions, the principal subsystems, and the power requirements for the accelerator.

The structure would approach 1 km in length and with rf gallery and shielding included would be of the order of 50 m wide.

The accelerating structures are:

i) Ion source, buncher and dc injector, referred to simply as injector in Fig. 1 which delivers protons at 0.25 MeV to the first rf structure.

ii) Drift-tube linac. This accelerates the particles up to energies where relativistic effects begin to be important.

iii) Coupled-cavity linac, a structure with greater efficiency for accelerating to the higher energies required. The transition, which also involves a threefold increase in rf frequency, would occur at about 150 MeV.

The accelerator is very similar in overall design to the existing Los Alamos Meson Physics Facility (LAMPF) accelerator. However LAMPF is designed for 1 mA average current and 800 MeV with 12% duty factor. The accelerator breeder thus represents a 40-fold increase in pulse beam current and would operate with 100% duty factor. Various linacs of lower energy operating as synchrotron injectors have delivered >200 mA in pulsed mode. The accelerator thus does not represent an overwhelming advance in performance characteristics.

Figure 4 suggests that the accelerator breeder could have the capacity to be internally self sufficient in electrical supply, the power developed in the target being adjusted to supply the electrical needs of the accelerator. The power requirements for the ion source, buncher and injector are ignored.

Whether the breeder would in fact be required to supply its own power or to take power from the mains, or even to produce some net power in addition to fissile material, would depend on many economic and design considerations that cannot be explored without a detailed design of the breeder and specification of the external energy system to which it is coupled. As mentioned above the thermal output can in principle be adjusted by controlling the fissile content in the target/blanket assembly. In any event, the fissile content would be maintained at a level sufficiently low to preclude criticality under any possible normal operating or accident conditions.

Figure 4 also suggests the major role played by rf technology in the accelerator breeder. Indeed, rf cost is one of the largest items contributing to total cost23).

2.2 Target/Blanket Assembly

Figure 5 shows schematically one simple target/blanket concept. Various other concepts have been developed19) but none have been carried through to detailed design. The figure is adequate only to indicate major design problem areas. A variant of the windowless liquid-metal target with horizontal beam entry, proposed by the Brookhaven National Laboratory20), may represent a more realistic approach.

The proton beam is delivered in an evacuated pipe and therefore a vacuum-to-target interface is required that can withstand the radiation damage produced by the 300 mA beam. To dissipate heat it will be necessary to defocus or otherwise spread the beam at the target.

The interface problem is handled in Fig. 5 by making the primary target the 44 wt% Pb, 56 wt% Bi eutectic alloy which melts at 125°C. The vapour pressure of this eutectic is compatible with maintaining an operational vacuum in the beam transport without a solid intervening window at the target.

The target liquid would be circulated to a heat exchanger. A flow rate of the order of 4 $Mg \cdot s^{-1}$ to dissipate the ∿200 MW of heat deposited locally would be required making for a formidable hydraulic design problem. This problem is avoided in other concepts by adopting a multiple lead-bismuth jet configuration20), a liquid-sodium-cooled staggered-pin target22) or a light-element-primary-heavy-element-secondary target21).

The integrity of the containment wall of the target presents another crucial design problem. The neutron source in the target of Fig. 5 is concentrated axially within about two geometric mean free paths (about 30 cm) from the entrance surface. The neutron production peaks at about 10 cm into the target and falls exponentially for greater depths24). The fast neutron flux for a target of 10 cm radius, say, would be of the order of 5×10^{15} $cm^{-2} \cdot s^{-1}$. While materials chemically compatible with lead-bismuth eutectic may be found[25)], it is clear that target design must include provision for frequent replacement of the target containment and possibly adjacent structures in the blanket in order to circumvent radiation damage effects.

The blanket configuration is envisaged to take advantage of experience in fast reactor blanket design. However, fuel management to accommodate inherent non-uniform primary neutron flux distributions and power level variations due to buildup of fissile material will be quite different from, and probably more difficult than, that for a fast reactor.

Shielding of the target/blanket assembly would resemble that of a fast reactor. Few, if any, high energy neutrons or other particles from the spallation reaction would penetrate the blanket material to create a shielding load beyond that for a reactor. Special steps would be required to shield against high-energy particles streaming along penetrations in the shield, in particular in the backward direction along the beam transport system.

The cooling system for the fertile blanket which would follow fast reactor technology would be capable of handling of the order of 1000 MW(th)*.

The cooling system for the Pb-Bi target would be required to dissipate of the order of 200 MW(th). In the conceptual design for the ING target cooling system[8)] which addressed similar problems, an intermediate liquid metal (NaK) was favoured between the Pb-Bi and the steam system.

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*th - <u>th</u>ermal power

The accelerator breeder cooling systems could feed a dedicated turbo-generator or, if the accelerator breeder were situated at a power reactor site the steam could be fed to a central turbo-generator.

2.3 Fuel Cycle Integration

The accelerator breeder would be employed in conjunction with a system of CANDU reactors operating on any of several variants of the thorium fuel cycle but typically involving ThO_2 feed with ^{233}U recycle and ^{235}U, Pu or ^{233}U topping. The 1 Mg/year output from the accelerator breeder would be sufficient to provide ^{233}U inventory for ∿0.25 GW(e)* per annum of increased capacity or topping enrichment for ∿10 GW(e) of reactors with a conversion ratio of 0.93. One accelerator breeder could thus supply fuel for a substantial electrical utility network.

Details of the cycle that might eventually be favoured depend on the economics and supply of feed and topping materials as well as on their practical accessibility, i.e. on the mechanisms in place for handling and deploying fissionable material to minimize proliferation and related hazards. One mechanism in principle compatible with accelerator breeding would be the internationally safeguarded energy center which might contain the accelerator breeder as well as fuel reprocessing and fabrication facilities. Shipment of fuel beyond the boundary of the center might dictate some form of denatured fuel cycle involving accelerator-bred ^{233}U.

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*e - electrical power

3. SAFETY

3.1 Accelerator

In routine operation the linear accelerator would present no hazard to the public and little to the operations staff. While large quantities of rf power are generated, its adequate isolation from the environment presents no serious problem. Residual beam spill along the accelerator will give rise to local radiation fields (γ-rays and neutrons) and to induced activity in accelerator components and surrounding structures. Housing of the accelerator in a tunnel with thick concrete walls will be necessary. It is anticipated that beam spill may be kept within levels low enough that hands-on maintenance of the shutdown accelerator may be feasible[26). However, it is unlikely that the accelerator tunnel could ever be made safe enough for personnel to be present during full-beam operation.

Loss of control of the beam will require shutdown mechanisms that activate in 5 μs or less if the integrity of the vacuum wall is to be protected[27). Since the residual activity induced in the wall by the beam in 5 μs will be small and localized and since the stored energy in the beam is only about 1 kJ no active material dispersal hazard of significant proportions can arise from beam-control failure.

Location of the accelerator in an area free of seismic activity will be necessary to maintain integrity and alignment of the accelerating structures.

3.2 Target/Blanket Assembly

The most significant safety feature of the target/blanket assembly is that it would be operated under conditions precluding criticality from fissile buildup or 'recriticality' from loss of coolant events. Other failure conditions of more mundane nature are possible as discussed below; their complete solution cannot be considered fully in the absence of a reference design.

Failure of the Pb-Bi circulation system coincident with failure of the accelerator fast shutdown mechanism could result in Pb-Bi vapour production with possible escape of radio-nuclides into the beam transport and accelerator structure. However, their escape into the outside environment would require a highly improbable coincident beam line rupture.

Rupture of the Pb-Bi circulation system would disperse volatile spallation products and metal vapour. Fast-acting monitors and fast dump systems would be provided to reduce the severity of such an event.

Failure of the emergency cooling system required for removal of the Pb-Bi decay heat could also lead to rupture and possible dispersal.

Failure of the blanket cooling system could lead to ruptures and leaking of fission products.

Redundant warning and shutdown systems, redundant heat removal systems, and hermetic containment structures may all be necessary to prevent or mitigate the consequences of such failures but all requirements seem likely to fall within state-of-the-art technology.

4.0 ENVIRONMENTAL CONSIDERATIONS

An exclusion area with a radius of the order of 1 km would be required to safeguard against air polution from residual volatile emissions, e.g. spallation-product iodine and xenon, from the vacuum pumps upstream of the liquid metal interface. Effluent cleanup systems would be installed as required.

Fast-acting accelerator-shutdown and Pb-Bi dump systems, redundant cooling systems and adequate containment structures would protect against radioactive releases caused by system malfunction as discussed in Section 3.

There is no prospect of widespread radioactive contamination from a criticality accident in the blanket since the fissile invertory would be kept sufficiently dilute as to rule out approach to criticality under any condition.

The potential for ground water contamination should be little different from that from power reactors in the 1000 MW(th) range and would be handled in a similar way.

The radioactive waste production from the Pb-Bi circuit would be only a small increment on that accumulated in any associated reprocessing plant or reactor system. On the basis of approximate calculations done for the ING target[8)], radioactivities with half-lives of one year or more e.g. 1.3 a ^{109}Cd, would be produced in quantities together totalling of the order of 10^6 curies (37 PBq) per year assuming a total Pb-Bi inventory of the order of 50 Mg. In addition, certain chemically noxious spallation products would be produced, e.g. of the order of 70 kg of mercury. These materials would be unlikely to pose problems of a new order of complexity to whatever waste disposal system would be in place for the associated conventional reactor and reprocessing systems.

Heat discharges to the environment from accelerator and turbo-alternator are indicated in Fig. 4.

The neutrons released into the blanket from the Pb-Bi target will result in destruction of <2 g of fertile material for each 1 g of fissile material produced[23]. This ratio happens to be almost the same for uranium and thorium blankets and a similar number is obtained if a ^{238}U target is used. By contrast, a uranium separation plant or converter reactor would process ∿200 g of fertile per gram of fissile material produced. In environmental terms this high efficiency for the accelerator breeder represents good resource utilization and calls for a minimal mining operation per unit of power produced.

Several laboratories have considered using a spallation target/blanket assembly for the burning of actinide and fission product wastes[28]. The practicability of this process needs further study based on detailed information of the production rates for various fission and spallation products in the assembly. If the use of the heavy actinides as the target material itself were practical an additional benefit might be realised from the increased neutron yield with mass number - such targets being more efficient in neutrons produced per beam proton even than uranium.

5. NON-PROLIFERATION CONSIDERATIONS

The accelerator breeder is compatible with the concept of a secure energy center containing fuel reprocessing and waste-management facilities as well as a nuclear power plant. It then effectively removes the necessity of transporting fissile material into the security area from external sources.

The possibility of avoiding (or minimizing) reprocessing of fuel rods by placing depleted uranium- or thorium-loaded rods in the accelerator breeder in order to build in the required fissile material for reactor operation and then transferring the rods to the reactor without reprocessing has been discussed[20,22]. This operation could form parts of a once-through throw-away cycle or a repeat-breed-burn cycle. However, much study is required to establish the practicability of such operations in the face of formidable fuel engineering and fuel management problems.

The accelerator breeder does not present an easy route for clandestine fissile material production because of its large size and cost, and the high-technology capability required for its construction and operation.

6. ECONOMIC AND COMMERCIAL FEASIBILITY

The cost of fissile material from an accelerator breeder can be estimated from the capital cost of the plant (primarily the accelerator and the target/blanket assembly) suitably amortized, plus operating and maintenance costs.* A calculation[2] of this type based on reasonable assumptions for the various costing parameters involved has shown that the accelerator breeder should be able to produce fissile material at a cost in the range \$50/g-\$100/g.

*To avoid the uncertainties of a fluctuating inflation rate these values and those for U and R discussed below are estimated assuming an inflation-free charge rate of 4%. It should be noted that, to reflect current inflation rates, the capital components of these values would be considerably increased.

Approximate fuel cycle comparisons[2)] based on a method by Critoph[29)] indicate that a cycle using ThO_2 with ^{233}U recycle and Pu topping (from the accelerator breeder) would likely be competitive with other cycles in a CANDU-PHW system when uranium price, U, and reprocessing and active fuel fabrication cost, R, both exceed ∿$300/kg for a fissile product charge of $50/g and when U and R both exceed ∿$500/kg for a fissile charge of $100/g. In each case R could vary above and below the value quoted but only if significant increases in U also obtain. Allowance of a 1 mill/(kW·h) cost differential in favour of the cycle to offset costs of early introduction of the accelerator breeder greatly increases the domain in U and R over which the cycle becomes economic.

7. UNIQUE SYSTEM CAPABILITIES AND CONSIDERATIONS

The accelerator breeder provides a method of ensuring fissile material supply independent of natural fissile or plutonium resources. As a breeder it achieves infinite effective breeding gain.

The heat produced by the spallation process and its concomitant fast fission reactions in a ^{238}U or ^{232}Th target/blanket assembly is comparable to that needed to supply the power to drive the accelerator. Any power shortfall could be made up if required by arranging that the accelerator breeder operate with some extra power generation from fissile material built up in the target. It would be desirable, however, to maintain fissile concentration at levels precluding criticality accidents.

The accelerator breeder offers the possibilities of a once-through throw-away cycle consuming fertile material only, and of re-enrichment of spent fuel without reprocessing.

Actinide waste disposal is no less feasible by accelerator breeder than it is by high-flux reactor or fusion reactor but if, in addition, the actinides could be used as target material the process offers the possibility of producing neutrons with efficiencies exceeding that of a uranium target.

B. TECHNICAL STATUS AND R/D REQUIREMENTS

Accelerator technology requires development to reach the beam current and energy required for accelerator breeding. However, no formidable problems are foreseen.

Development work is required to provide the best method of launching the beam through the early stages of acceleration with the emittance required for minimum beam spill at higher energies. This includes development of an ion-source and a dc column that are reliable and free of high-voltage breakdown problems, a "clean" buncher system, and a low-energy drift tube linac with minimum beam spill30).

Attention to computer control of all accelerator systems to aid performance optimization is required. Close attention to ways of achieving overall system reliability in component design and in systems engineering is also required.

Development of efficient, reliable r.f. systems, including cheap reliable klystrons or their equivalent is essential.

Much development is required to provide target/blanket assemblies with good neutron economy, high fuel conversion, good heat transfer and minimal radiation damage.

Acquisition of necessary target/blanket technology is dependent upon further extension and improvements of spallation cross sections and neutron spectral data at high bombarding energies and the determination of fissile production rates for realistic target/blanket assemblies.

Structural materials suitable for the high flux region in the target must be identified and their properties measured for a wide range of operating conditions. Target designs permitting easy remote access for changing these critical parts of the target are required.

Much work both theoretical, and where possible experimental, to overcome problems in blanket fuel integrity, irradiation uniformity and management schedules is required.

9. AECL PROGRAM

9.1 Present Program

Two test facilities, the High Current Test Facility (HCTF) and the Electron Test Accelerator (ETA) are used to study accelerator structures and performance with high-current, 100% duty factor beams.

The HCTF is designed to study problems associated with the 100% duty factor drift-tube linac, in particular the injection and acceleration of a proton beam with a current set by the space-charge limit of the structure (near 50 mA). It consists of an ion source, 750 kV injector and a single Alvarez tank with a design output of 3 MeV.

The ETA is an electron-loaded model of one version of the coupled-cavity structure that could be used in a proton linac. It consists of a low-energy graded-β structure and a $\beta=1$ structure combined to give an output energy of 4 MeV and is planned for operation at 50 mA.

Experiments are in progress using the TRIUMF accelerator to measure neutron leakage and fertile-to-fissile conversion rates in small target assemblies of lead, uranium metal, thorium metal, and natural UO_2.

An rf tube development program has been directed toward developing more efficient dc-to-rf converters. This program is temporarily in abeyance.

Cooperative activities with U.S. laboratories, in particular LASL, currently involving secondment of staff to work on accelerator problems and cooperative fertile-to-fissile conversion experiments are underway.

9.2 Future Developments in Short Term

An ion source and injector test facility is being set up to

- test high current ion sources to 500 mA proton output
- develop and test techniques for beam conditioning, ion species selection, emittance filtering, prebunching, chopping, space-charge neutralization and beam diagnostics.

- study column high current conditioning
- develop adequate low-energy beam transport and dumps
- assess system reliability, stability, and component life.

Other development tasks anticipated, resources permitting, are as follows:

A theoretical beam dynamics study will be undertaken.

New low-energy structures giving improved beam focussing will be studied.

Control systems capable of handling run-up of the beam from zero to full current will be studied.

The rf tube development program will be reactivated to include theoretical analysis, construction and testing of experimental tubes and acquisition of special technologies such as oxide-coated cathode fabrication.

Development of calculational methods needed in conceptual design of accelerator breeder target/blanket assemblies will be extended to include power distribution, fertile conversion ratio, radiation damage etc.

The fertile-to-fissile conversion experiments will be extended to higher energies and to involve a wider range of target assemblies and to include the effects of structures and coolants.

Materials problems in the target/blanket area will be assessed and where possible studied experimentally.

Coolant technology and fuel engineering appropriate to the systems will be studied and a target/blanket reference design evolved.

Cooperative R&D programs with other interested laboratories will be vigorously pursued.

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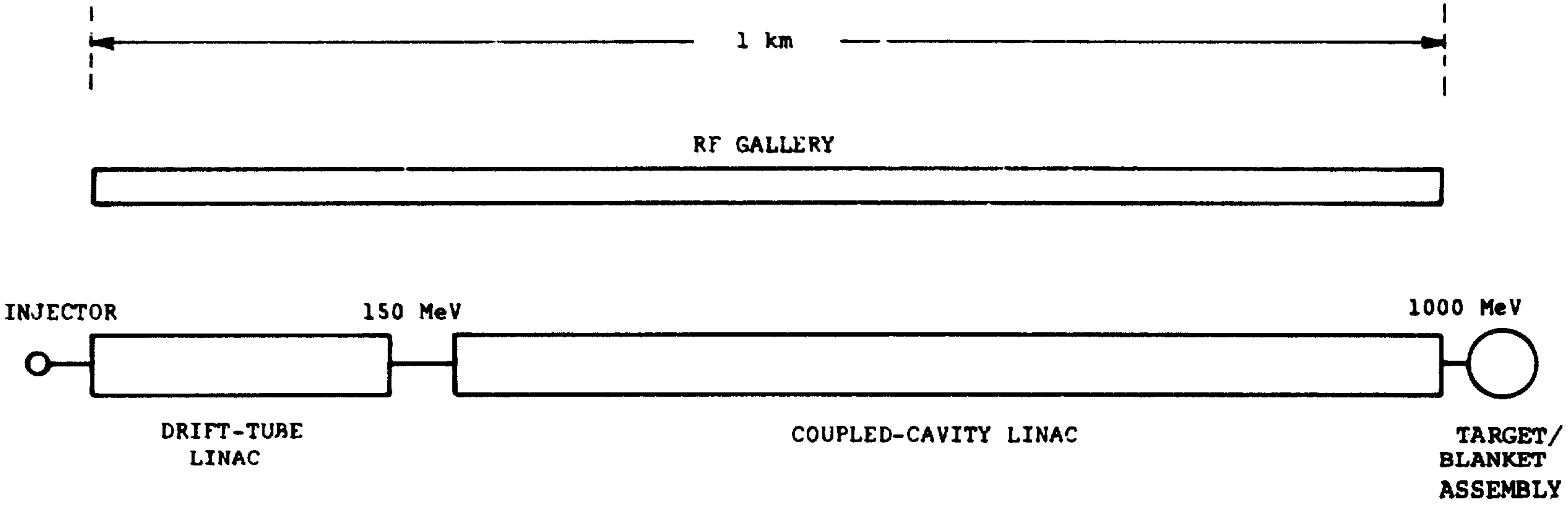

Fig. 1 Main components of a demonstration accelerator breeder.

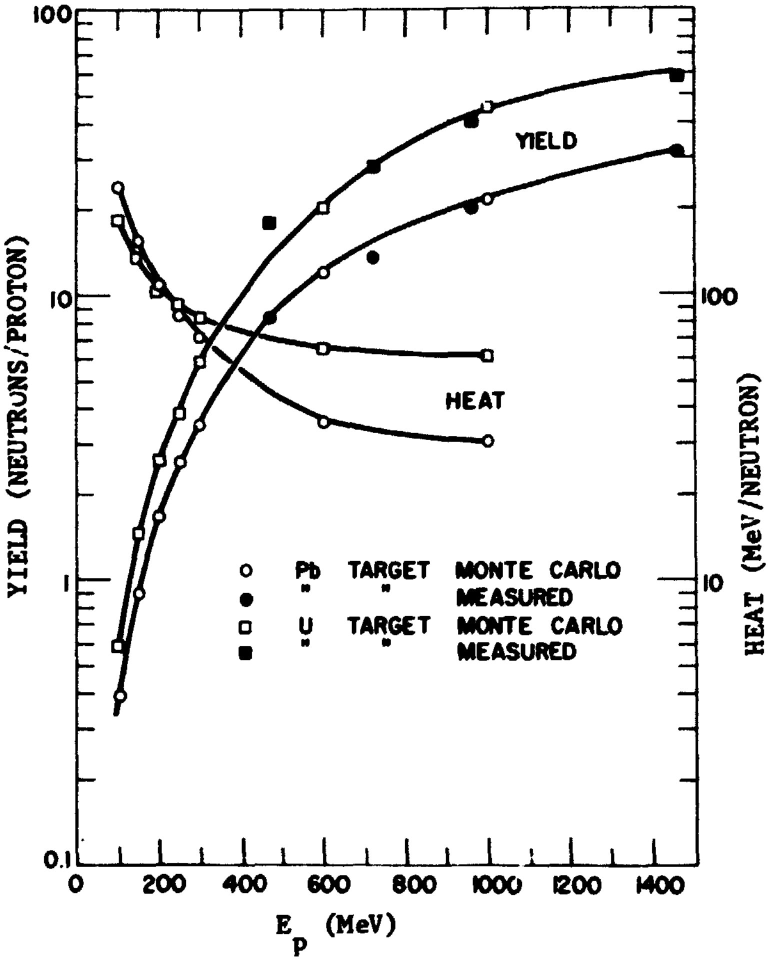

Fig. 2 Measured and calculated neutron yields and calculated heat production vs. proton energy for 20 cm diameter lead and fully depleted uranium targets$^{31)}$.

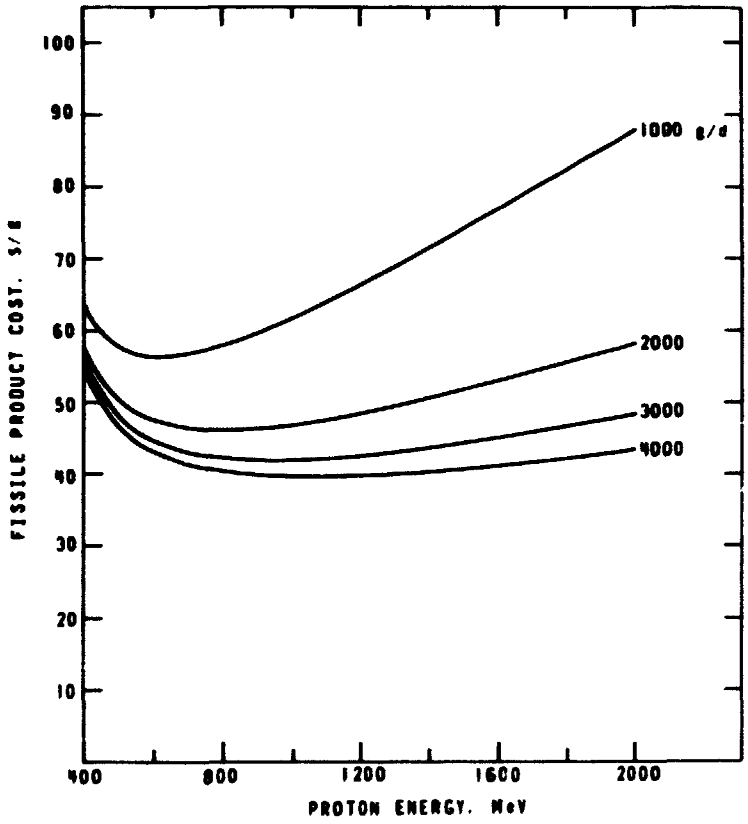

Fig. 3 Calculated unit fissile product costs for production rates 1000 to 4000 grams per day vs. proton energy. The principal assumptions are: electrical power costs, $0.007/kW·h); target costs included in the electrical power costs; interest and depreciation, 10% per year; rf equipment capital $350/kW; accelerator unit length cost, $60,000/m; maximum peak accelerating field, 2 MV/m, averaged over the accelerator length.

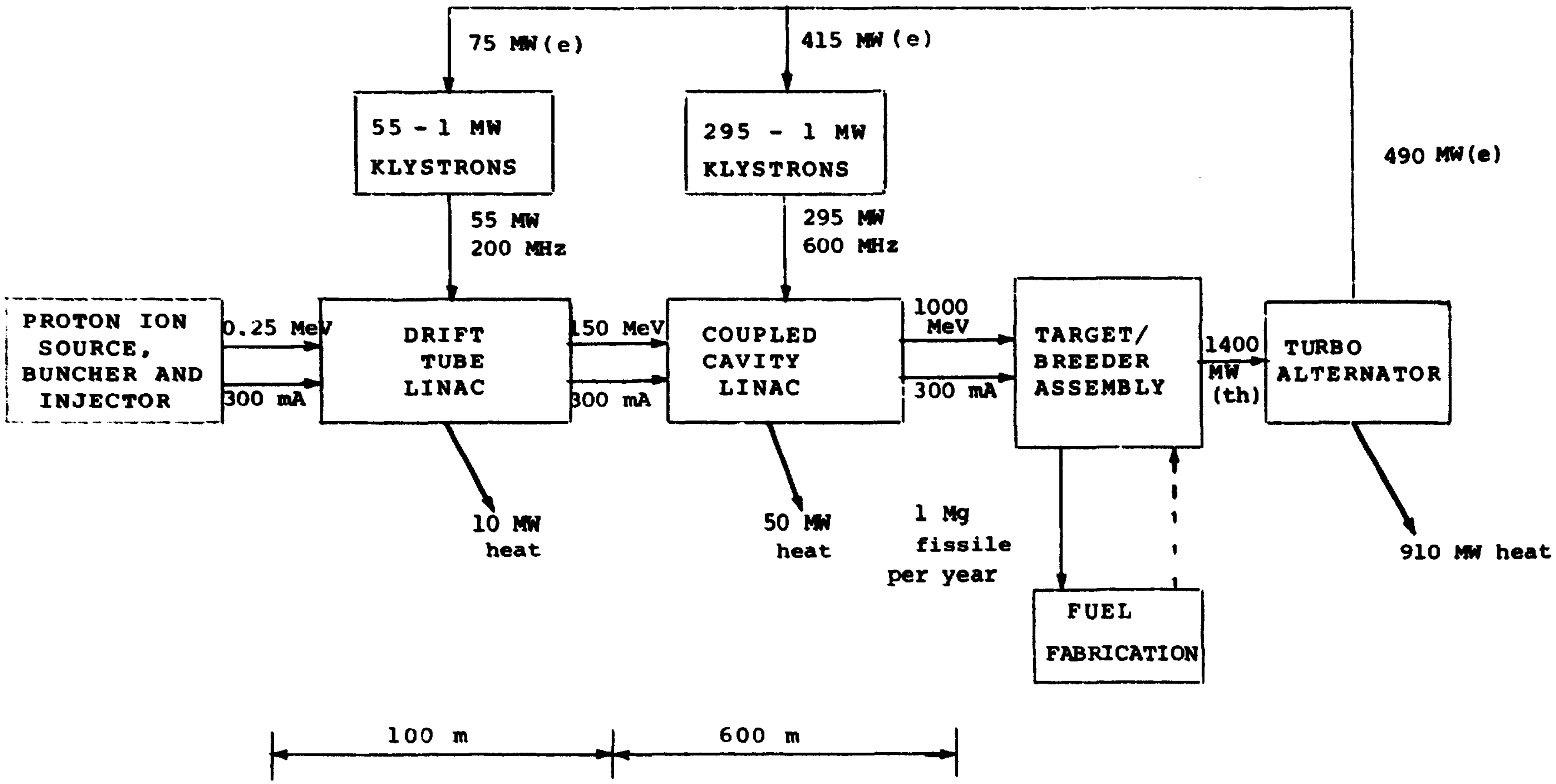

Fig. 4 Major subsystems and power requirements

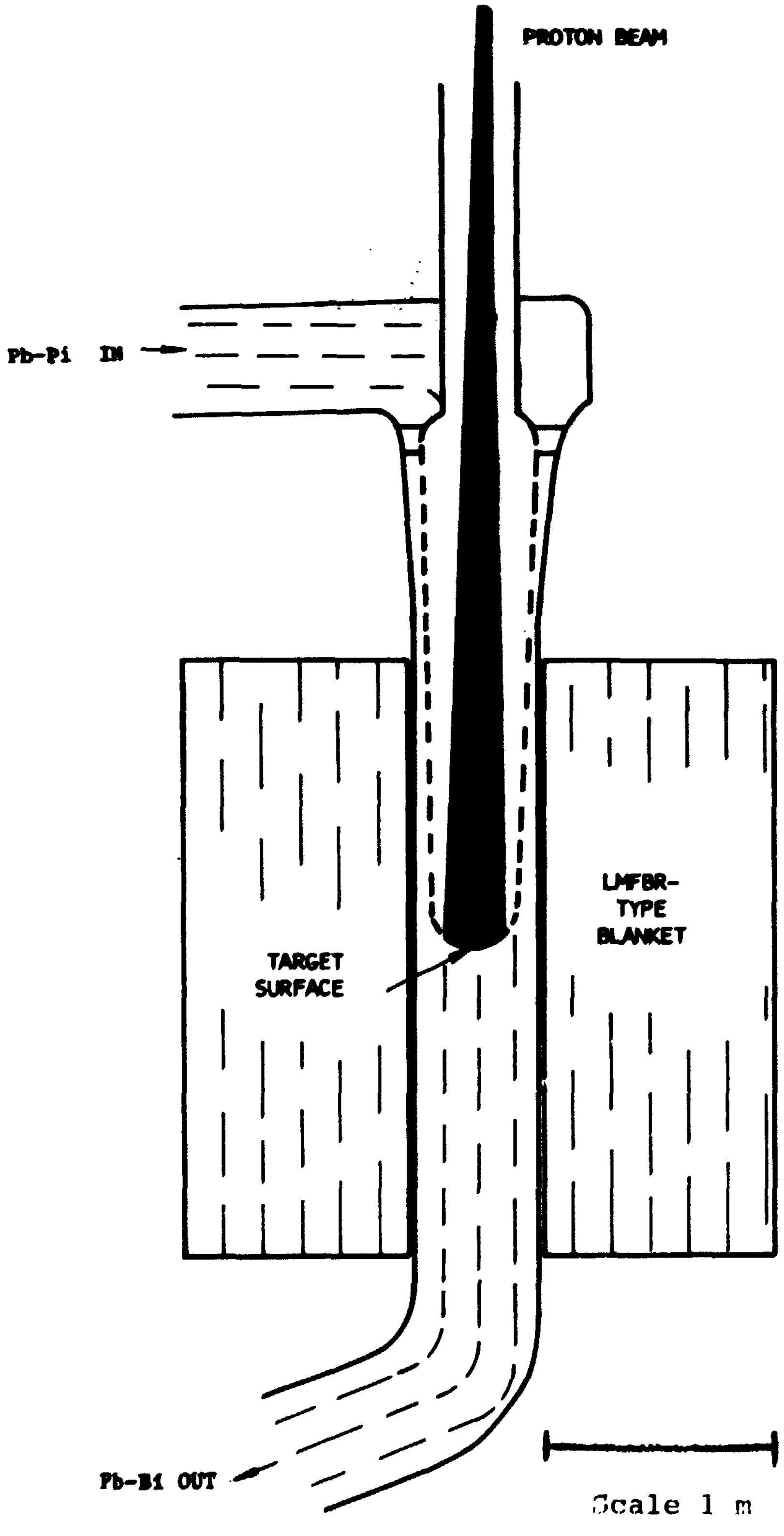

Fig. 5 Schematic diagram of a windowless target of liquid metal surrounded by a liquid-metal cooled blanket.